N94-34987

Mechanisms of Flow Control with the Unsteady Bleed Technique

D.R.Williams, M.Acharya and J.Bernhardt

Fluid Dynamics Research Center
Illinois Institute of Technology
Chicago IL 60616

Introduction

The unsteady bleed technique (a.k.a. internal acoustic forcing) has been shown to be an effective method for control of separation on low Reynolds number airfoils, blunt-end cylinders aligned axially with the flow, cylinders aligned perpendicular to the flow and forebody geometries at high angles of attack. In many of these investigations, the mechanism for the control has been attributed to enhancement of the shear layer (Kelvin-Helmholtz) instability by the unsteady component of the forcing. However, this is not the only possible mechanism, nor may it be the dominant mechanism under some conditions. In this work it is demonstrated that at least two other mechanisms for flow control are present, and depending on the location and the amplitude of the forcing, these may have significant impact on the flow behavior.

Experiments were conducted on a right-circular cylinder with a single unsteady bleed slot aligned along the axis of the cylinder. The effects of forcing frequency, forcing amplitude and slot location on the azimuthal pressure distribution were studied. The results suggest that a strong vortical structure forms near the unsteady bleed slot when the slot location is upstream of the boundary layer separation point. The structure is unsteady, since it is created by the unsteady forcing. The "vortex" generates a sizeable pressure spike ($Cp = -3.0$) in the time-averaged pressure field immediately downstream of the slot. In addition to the pressure spike, the boundary layer separation location moves farther downstream when the forcing is activated. Delay of the separation is believed to be a result of enhancing the Kelvin-Helmholtz instability. When forcing is applied in a quiescent wind tunnel, a weak low-pressure region forms near the slot that is purely the result of the second-order streaming effect.

Background

Sigurdson and Roshko(1985) used an acoustic driver to excite the axisymmetric shear layer and separation bubble formed at the blunt end of a cylinder aligned axially with the flow. They identified two fundamentally different mechanisms by which the unsteady forcing modified the flow. In the first mechanism the unsteady forcing enhanced the Kelvin-Helmholtz instability in the separating shear layer. A second mechanism involved forcing at wavelengths comparable to the separation bubble height, which enhanced a "shedding" type of instability for the entire bubble.

Huang, Maestrello and Bryant (1987) demonstrated the effectiveness of internal acoustic forcing as a flow control technique for reattaching the separated boundary layer on a low Reynolds number airfoil at high angles of attack. Their unsteady bleed slot was located near the leading edge of the airfoil. They found that lift was enhanced and stall was delayed when the separating shear layer was perturbed by sound at frequencies comparable to those found in the shear layer.

Williams and Economou (1987) used unsteady bleed to control the Karman vortex formation behind a circular cylinder at Reynolds number 370. This work was extended by Williams and Amato (1988 a,b). The unsteady bleed was shown to generate a low pressure region near the body and momentum was added to the flow by the second-order streaming effect.

In another experiment on an airfoil, Huang, Bryant and Maestrello (1988) showed spectral evidence that the wake structure responded to the excitation frequency when the unsteady bleed slot was located near the trailing edge of the airfoil. In this case the most effective frequency was near the vortex shedding frequency. The control mechanism was attributed to the generation of large-scale vortical structures which enhanced entrainment and modified the pressure recovery region.

Williams, et al. (1989) used the unsteady bleed technique to control the forebody vortex formation around slender cone-cylinder bodies at high angles of attack. With the correct forcing conditions it was possible to eliminate the strong forebody vortex and convert the asymmetric velocity field to a symmetric velocity field. In this case, the forebody vortex is steady, so there is no natural frequency to scale the control. Therefore, the control mechanism was attributed to a direct modification of the mean flow. In particular, the rectified pressure field and the momentum addition by the streaming effect were believed to be the controlling factors.

Hsiao, et al (1989) showed that the flow around airfoils and cylinders could be influenced by forcing through a slot aligned with the cylinder axis or airfoil span. They found that the forcing was most effective when placed near the separation line. As in other experiments on airfoils and cylinders, the data indicated a sensitivity to forcing frequency. This provided evidence that the unsteady component of the forcing enhanced entrainment and delayed separation. However, their pressure measurements on a cylinder showed a relatively large pressure spike near the unsteady bleed slot that could not be explained by enhanced entrainment.

We became interested in the nature of this pressure spike, because it represented a large percentage of the modified pressure field. The following experiment was designed to explore the mechanisms by which the unsteady bleed technique modified the flow.

Experimental Arrangement

The tests were conducted on a 6.35 cm diameter cylinder mounted vertically in an open return wind tunnel. The cross section of the wind tunnel was 40 cm by 61 cm. End plates were placed 41 cm apart, which gave an aspect ratio of 6.4 for the cylinder. The unsteady bleed forcing was generated by a 30 cm diameter loudspeaker mounted on top of the wind tunnel and connected by a pipe to the interior of the cylinder. The loudspeaker was driven by a 60 Watt Dynaco amplifier and a Hewlett-Packard 3311A function generator. Measurements of the pressure inside the cylinder showed the pressure fluctuation to be sinusoidal. The power delivered to the speaker by the amplifier was measured with an r.m.s. voltmeter and ammeter. Although the power varied with amplitude and frequency, it was always less than 25 Watts.

A schematic of the cylinder and the forcing arrangement is shown in Figure 1. The slot was 8 cm long and 0.1 cm wide and was centered along the span of the cylinder. Because the slot is the only opening in the forcing system, there is no net mass addition to the flow over the forcing cycle. For one half of the cycle fluid was ejected from the cylinder, then during the suction phase of the cycle fluid was drawn back in to the cylinder.

Results

In order to quantify the amplitude of the unsteady bleed disturbance, both velocity measurements and sound pressure level (SPL) measurements were made next to the slot in the cylinder wall with no external flow. The hot-wire anemometer probe was placed in the exit plane of the slot. Although the hot-wire experiences reverse flow during the suction side of the forcing cycle, the reverse flow signal was distinct from the outflow phase of the cycle, so the signal could be correctd. The r.m.s. velocity fluctuation level computed for this signal is shown in Figure 2a as a function of the frequency at different r.m.s. voltage levels applied to the loudspeaker. The data show that the r.m.s. velocity level does not increase monotonically with the forcing frequency. At lower voltage amplitudes to the speaker, the r.m.s. velocity decreases as the frequency is increased from 20 Hz to

120 Hz.

The sound pressure level was measured under the same forcing conditions with a B&K sound pressure level meter placed perpendicular to the exit plane of the slot. The data shown in Figure 2b have a monotonic increase with frequency from 20 Hz to 240 Hz.

The differences in the trends with increasing frequency allow us to separate the effect of the SPL from the velocity fluctuations. The data presented in Figure 3 show the pressure distribution around the azimuth of the cylinder at two different forcing frequencies 40 Hz and 140 Hz where the r.m.s. voltage of the speaker was kept constant at 2.0 volts r.m.s. The freestream speed was 5.27 m/s. Although the effect of the forcing produces a significant change in the pressure distribution, it is clear that very little difference occurred between the two pressure distributions. From Figures 2a and 2b we see that the velocity amplitude decreases slightly from 6.0 m/s to 5.5 m/s, while the SPL increases from 95 dB to 106 dB at the corresponding forcing conditions. It is apparent from this comparison that the control effect follows the behavior of the velocity fluctuations more closely than the SPL. It is highly unlikely that sound plays a significant role in the flow control mechanism.

Effect of Forcing on Azimuthal Pressure Distribution

The term "acoustic forcing" implies that the control mechanism occurs by a linear wave process. However, the following results indicate that this is not the case. Figure 4 shows pressure measurements taken with forcing at 240 Hz, SPL at 121 dB and the r.m.s. velocity fluctuation level at 14 m/s, but with *no flow* in the wind tunnel. (The pressure coefficient has been normalized in this plot by a dynamic pressure of 0.06694 in. w.c. for comparison with the other data.) It is clear that the mean pressure field around the slot is lower than the ambient pressure. This is a nonlinear effect resulting from the rectification of the unsteady pressure signal, and is analogous to the streaming phenomenon. A discussion of the rectification effect can be found in the paper by Williams and Amato (1988b).

The disturbances created by the loudspeaker must couple somehow with the flow field to create the vortical disturbances that enhance entrainment and delay separation. The r.m.s. velocity fluctuation level associated with a 120 dB sound wave is only 0.05 m/s. In contrast, the velocity fluctuation measured by the hot-wire anemometer is three orders of magnitude larger than the velocity associated with the sound wave. Such a large velocity fluctuation could only come from the "pumping" of fluid by the displacement of the loudspeaker cone. We believe this is the primary source of the vortical disturbance, not the acoustic field.

The azimuthal pressure distributions obtained with the slot positioned at -30^{o}, 30^{o}, 45^{o}, 75^{o} and 110^{o} from the forward stagnation line are shown in Figure 5, corresponding to a freestream speed of 5.27 m/s. The forcing conditions are the same in all cases, frequency 240 Hz and r.m.s velocity 14 m/s. The most obvious feature is the large pressure spike associated with the forcing slot. The change in Cp from the undisturbed value is approximately $\Delta Cp = -2.5$ at the first pressure tap downstream of the slot. This is followed by a steep increase and overshoot in pressure at the next two pressure taps. We believe this is the time-averaged signature of a periodic vortex-like disturbance generated by the interaction of the unsteady forcing field with the flow around the cylinder. We suspect that the "vortex" forms during the suction phase of the forcing cycle, then is "released" during the ejection phase, although this is still being investigated. Provided the unsteady bleed slot is upstream of the separation point, the pressure spike has the same shape, irrespective of the slot location. The same behavior is likely to occur with unsteady bleed control applied to airfoils upstream of separation. If such strong localized pressure spikes can be formed by the forcing alone, then substantial changes in airfoil performance are possible.

Figure 5e shows that when the forcing slot is beyond the separation point, then the large pressure spike does not form. The flow across the slot in the separated region is too slow for the interaction with the forcing flow to produce a strong "vortex". However, the pressure distribution between $\Theta = 70^{o}$ and 125^{o} indicates that separation was delayed. In this situation we believe that the flow control mechanism is by enhanced Kelvin-Helmholtz instability (K-H effect) described by other investigators. The K-H effect can be seen in each case shown in Figure 5. It is quite interesting that the pressure modification appears to be the superposition of the pressure spike at the slot location and the K-H effect. This observation supports the notion that these control mechanisms are fundamentally different mechanisms.

Conclusions

The unsteady bleed technique and internal acoustic forcing are synonyms for the same localized flow control technique. Measurements of the sound pressure level and the r.m.s. velocity amplitude at the slot have shown that the dominant disturbance is associated with the "pumping" of fluid by the loudspeaker, not the acoustic wave.

Pressure distributions obtained around the cylinder show three independent mechanisms are present that modify the flow. The weakest is the "streaming" effect created by the rectification of the unsteady pressure field at the bleed slot. This is likely to be insignificant in most cases unless the forcing amplitude is very strong. The second mechanism is a strong "vortex-like" disturbance created by the interaction between the forcing flow and the flow around the body. This resulted in a very strong pressure spike immediately downstream of the slot. The third mechanism is the enhancement of the Kelvin-Helmholtz instability in the separating shear layer, which produced a change in the pressure field slightly weaker than the pressure spike.

The latter two mechanisms will likely be present on all types of bodies in which the unsteady bleed technique is applied. The relative importance of the two will depend on the details of the forcing configuration, such as the location of the bleed slot and the forcing amplitude.

Acknowledgements

Special thanks go to Z. Grabavac and S. Mitus for their expert design and construction of the model and for their preliminary experiments. This experiment was conducted with the support of the Air Force Office of Scientific Research under contract F49620-86-C-0133, monitored by Capt. H Helin and Dr. J. McMichael.

References

Huang, L.S., Maestrello, L. and Bryant, T.D. 1987 "Separation Control Over an Airfoil at High Angles of Attack by Sound Emanating from the Surface", AIAA paper no. 87-1261, presented at 19th Fluid Dynamics, Plasma Dynamics and Lasers Conf. Honolulu, HA.

Huang, L.S., Bryant, T.D. and Maestrello, L. 1988 "The Effect of Acoustic Forcing on Trailing Edge Separation and Near Wake Development of an Airfoil", AIAA paper no. 88-3531-CP, presented at 1st National Fluid Dynamics Cong. Cincinnati, OH.

Hsiao, F.B. Liu, C.F. and Shyu,J.Y. 1989 "Control of Wall-Separated Flow by Internal Acoustic Excitation", AIAA paper 89-0974, presented at 2nd Shear Flow Control Conf., Tempe AZ.

Sigurdson, L.W., and Roshko, A. 1985 "Controlled Unsteady Excitation of a Reattaching Flow", AIAA paper no. 85-0552, presented at Shear Flow Control Conf., Boulder CO.

Williams, D.R. and Amato, C.W. 1988a "Unsteady Pulsing of Cylinder Wakes", AIAA paper 88-3532-CP, presented at 1st National Fluid Dynamics Cong. Cincinnati, OH.

Williams, D.R. and Amato, C.W. 1988b "Unsteady Pulsing of Cylinder Wakes", Frontiers in Experimental Fluid Mechanics (ed. M. Gad-el-Hak) Lecture Notes in Engineering, Vol. 46.

Springer.

Williams, D.R., El-Khabiry, S. and Papazian, H. 1989 "Control of Asymmetric Vortices around a Cone-Cylinder Geometry with Unsteady Base Bleed", AIAA paper 89-1004, presented at 2nd Shear Flow Conf. Tempe, AZ.

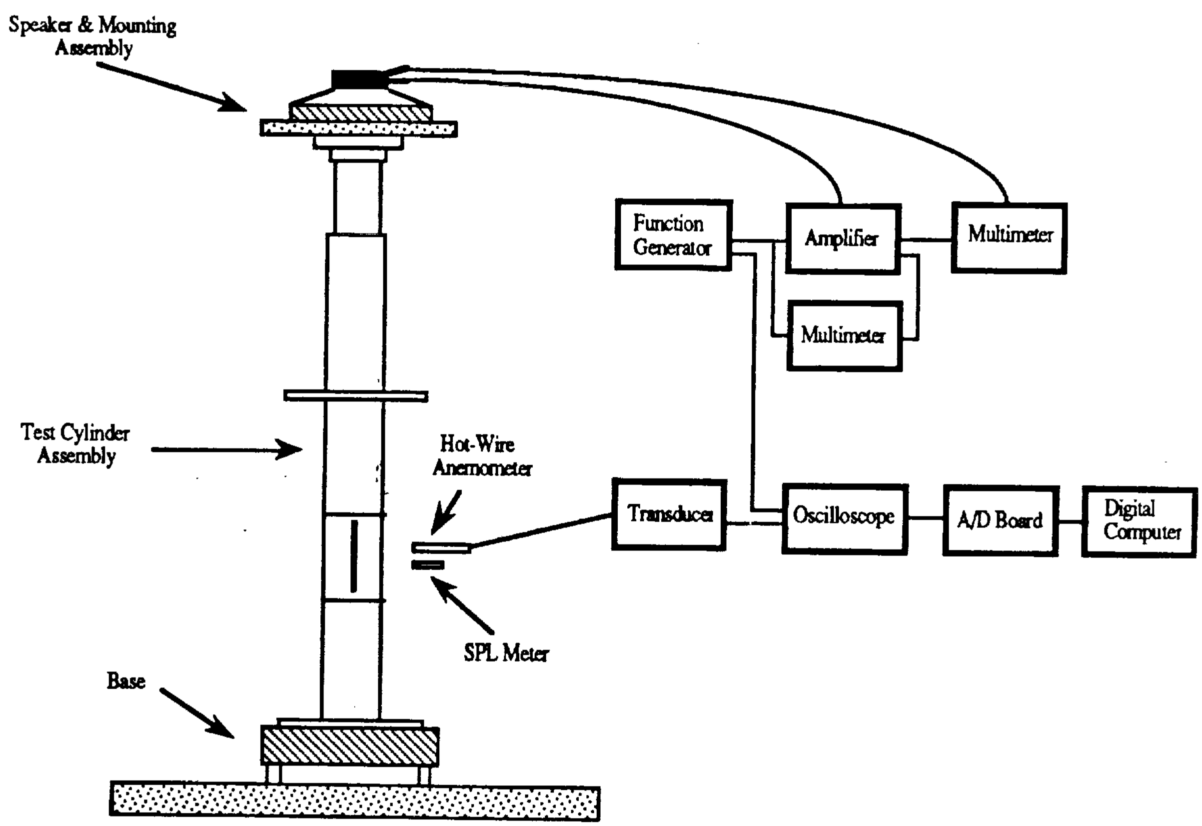
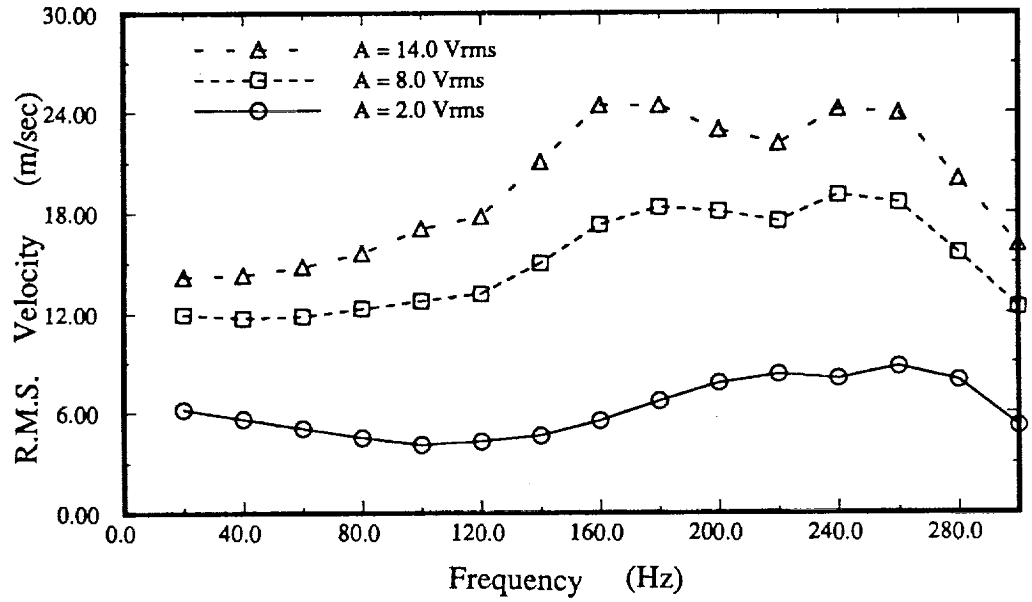


Figure 1 - Schematic of the cylinder and unsteady bleed apparatus.

(a)



(b)

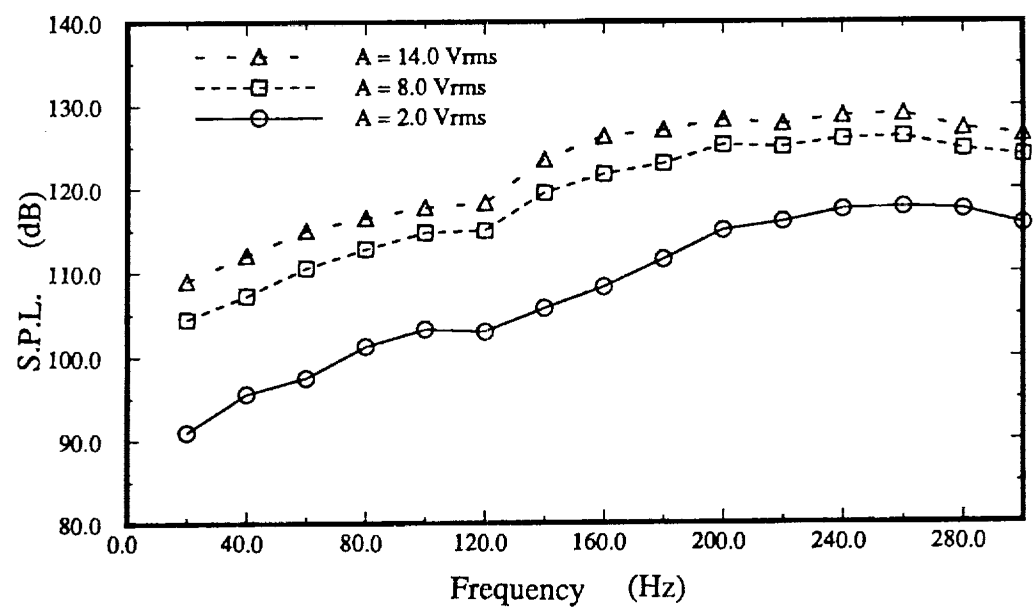


Figure 2 - (a) r.m.s. velocity at the exit of the slot with different forcing frequencies and voltages. (b) Sound pressure level at the exit of the slot for the same forcing conditions in (a).

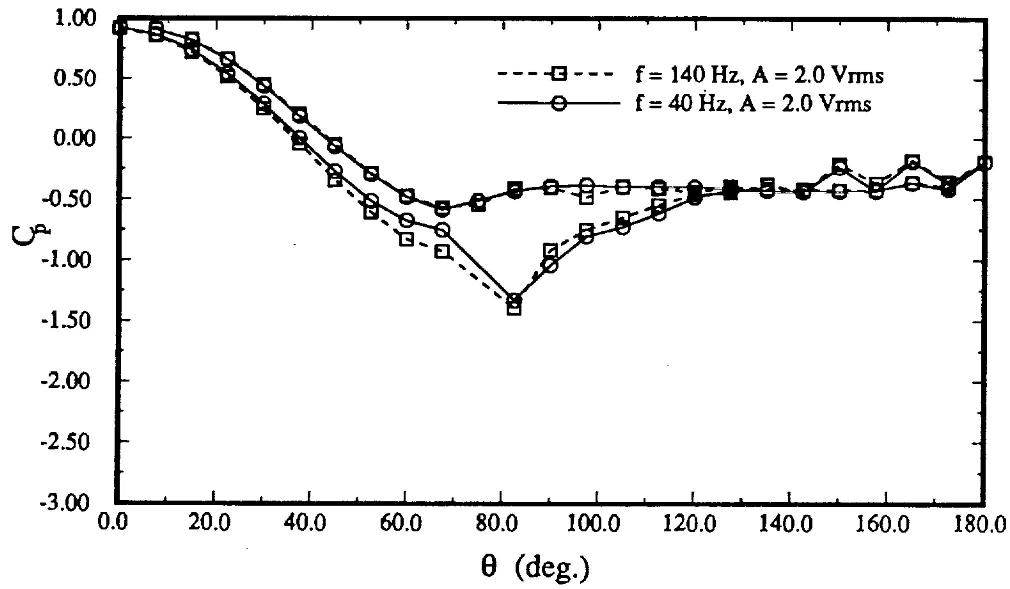


Figure 3 - Comparison of the azimuthal pressure distribution with two different forcing frequencies, 40 Hz and 140 Hz.

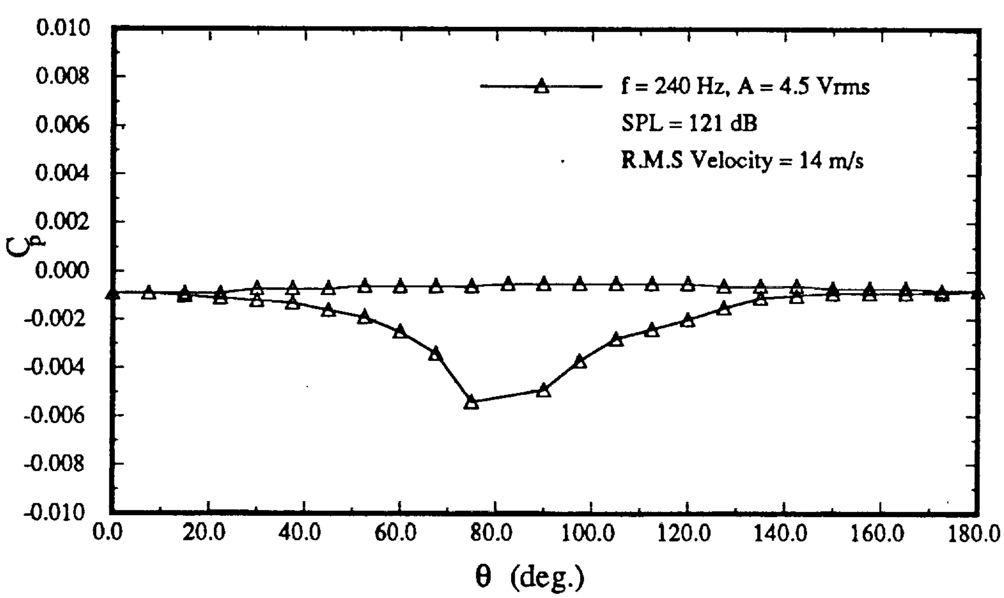


Figure 4 - Azimuthal pressure distribution obtained with no external flow in the wind tunnel. Forcing frequency 240 Hz, r.m.s. velocity 14 m/s.

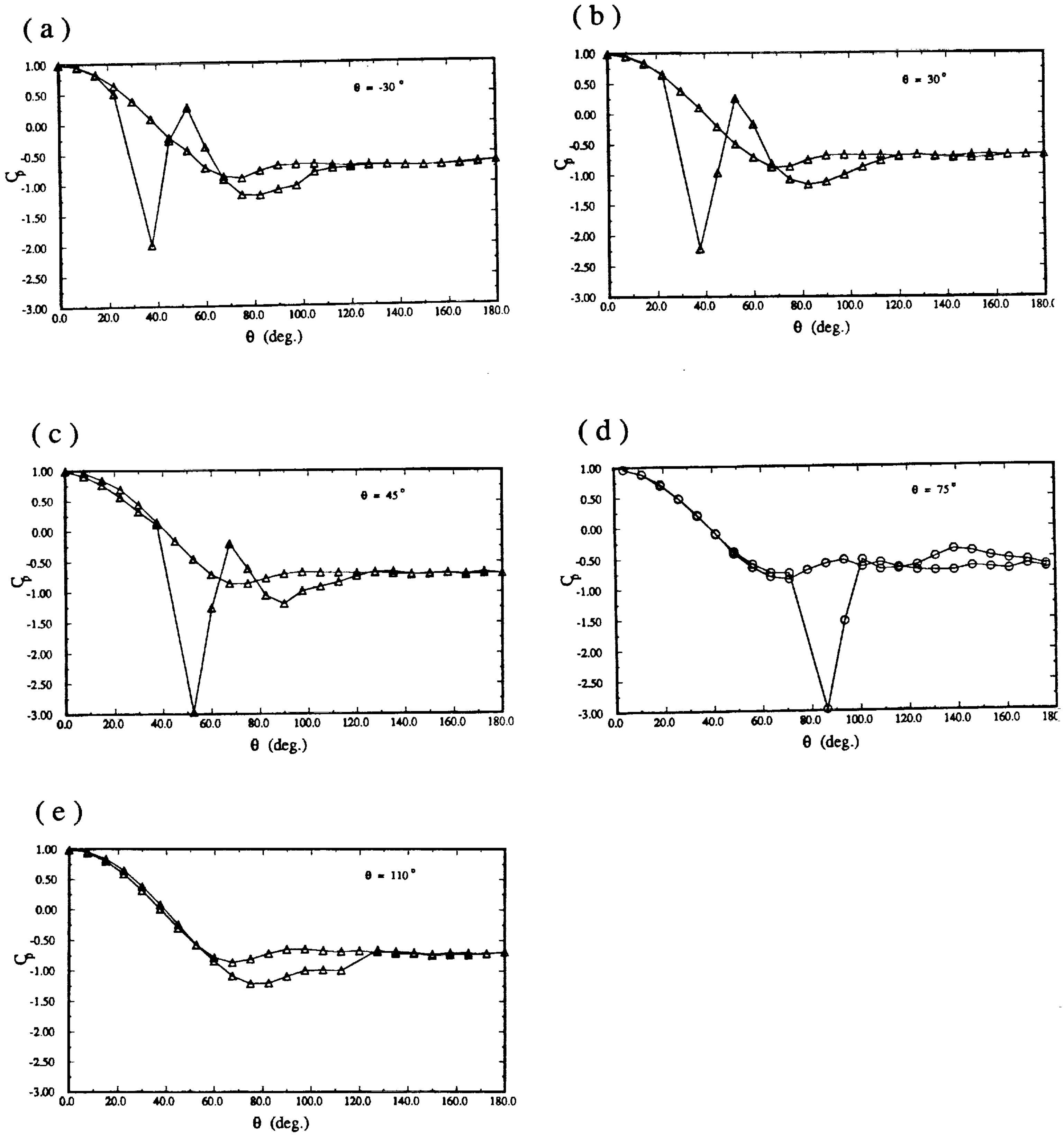


Figure 5 - Pressure distributions obtained with the unsteady bleed slot located at Θ = -30°, 30°, 45°, 75° and 110°. Forcing frequency 240 Hz, r.m.s. velocity 14 m/s.

Conclusions

Unsteady bleed and internal acoustic forcing are synonyms for the same phenomenon.

Acoustic effects are insignificant in this type of control.
The effects of forcing scale with the velocity fluctuation level, not the SPL.

The second-order "streaming" effect is present, but insignificant.

The forcing flow interacts with the external flow to produce a localized, large-amplitude pressure spike.

The effects of enhanced K-H instability appear to be present.
Measurements of the velocity spectrum are required.